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Erik Antonsen (U. of Illinois) et al., "Herriott Cell Interferometery for Millimeter-Scale Plasma Measurements"

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Herriott Cell Interferometry for Millimeter-Scale Plasma Measurements

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ABSTRACT

A Herriott Cell consists of two concave mirrors positioned on opposite sides of plasma so as to create multiple laser paths through the plasma. Added to a traditional interferometry diagnostic, the Herriott Cell multiplies the effective path length through the medium and thereby increases instrument resolution. Previous work validated the use of Herriott Cells in interferometer applications where the numerous mirror reflections will significantly degrade the phase front quality. The previous work used a planar configuration where collimated beams were retro-reflected across the exit plane of a plasma thruster. The current work extends the Herriott Cell capability to a point configuration. In this geometry the multi-pass beams converge near a single point within the plasma, useful for performing density measurements in very small scale length plasmas. Ray tracing analysis is used to illustrate example measurement geometries attainable with the instrument. It is shown that the configuration results in two convergence points for the laser paths, which somewhat complicates the interpretation of the experimental data. The diagnostic capability is demonstrated with measurements of the electron and neutral densities in the plasma exhaust of a Micro Pulsed Plasma Thruster. The measurements are validated with similar, lower resolution measurements, obtained using a single-pass interferometer.

Topic Category 9: Interferometry, Polarimetry

1. INTRODUCTION

Plasma and neutral density measurements are critical in the development of the Micro Pulsed Plasma Thruster (MicroPPT).[1,2] The MicroPPT is a spacecraft propulsion device that uses a pulsed (~10 μs) electrical surface discharge across the face of a solid Teflon™ propellant. The discharge ablates a small amount of material (~1 μg), ionizes it to plasma, and electromagnetically accelerates it to create thrust. Following the pulsed discharge a larger mass (~4 μg), of neutral vapor is emitted from the device on a much longer time scale (~1 ms). The electron and neutral density measurements are needed to better understand the conversion from solid Teflon™ propellant to plasma accelerant. In addition, exit plane density measurements are needed to develop and verify models[3,4] of interaction between the spacecraft and the exhaust plume. The small plasma volume of the MicroPPT creates a significant diagnostic challenge. Broadband intensified emission images show a plasma plume about 6-mm diameter and 20-mm long. For material probes, such as electrostatic or magnetic field probes, the characteristic length of the probe is comparable to or larger then the MicroPPT plasma volume. For interferometric techniques to measure density, the measurement resolution is constrained by the short scale length of the plasma. Since the interferometer measures a phase shift proportional to the product of the density and the laser path length through the plasma, the fundamentally short path length results in excessive measurement uncertainty for the line-averaged plasma density.

To address this problem, a Herriott Cell interferometer is used and a technique employing a 'point measurement' is developed. This technique converges multiple laser passes in a small area (~4-5-mm), thereby providing increased laser path length within the plasma.

This has the effect of increasing instrument resolution approximately linear with the increased number of passes. For larger plasma volumes the increased resolution can be achieved with minimal impact on the spatial resolution. For the small scale-length plasma of the MicroPPT, the Herriott Cell in a point configuration is used to measure the total electron or neutral density at the exit plane of the 6-mm diameter thruster.

Previous work[5] has shown that the Herriott Cell can also be used to combat the effects of mechanical vibrations on interferometric measurements. Vibrations cause physical path length changes through motion of optical components, thereby increasing measurement uncertainty that can mask actual density measurements. While electron density can be separated from this effect through the use of a second laser frequency, neutral density measurements remain susceptible, especially as time increases. Since the largest contribution to mechanical vibration is not between the Herriott Cell mirrors, adding passes between the mirrors increases laser path length to increase the signal of the neutral density induced phase shift relative to the noise of the phase shift introduced by mechanical vibrations.

The Herriott Cell allows a number of beam geometries useful for various applications in interferometry. Generation of these geometries and the question of phase front degradation over a large number of reflections from the curved surfaces of the Herriott Cell mirrors are addressed in a previous paper.[6] This work is a unique development from the retro-reflecting techniques used in Ref. 6. The point technique requires focusing optics external to the Herriott Cell that are unnecessary in the previous work. Changes in

number of cell reflections are effected through mirror tilt and entrance angle as opposed to mirror separation distance. Additionally, operation with converging-diverging beams and the possibility of refractive effects due to high density in a small plasma volume warrant a separate explanation of this diagnostic technique.

This paper focuses on the specific benefits of the Herriott Cell in a point configuration applicable to the spatially small plasmas generated by the MicroPPTs. Section 2 describes the apparatus. Ray tracing analysis is used to illustrate converged beam geometries enabled by the Herriott Cell. In Section 3, the resolution increase of the system is discussed along with practical setup considerations. In Section 4, the diagnostic capability is demonstrated with measurements of the electron and neutral densities in the plasma exhaust from MicroPPTs. The measurements are validated with similar, lower resolution measurements, obtained using a two-color, two-pass interferometer.

2. Apparatus

2.1 Herriott Cell Interferometer

A schematic of the diagnostic layout is shown in Fig. 1. The lasers, acousto-optic modulator, optics, and detectors are positioned on an air-leveled optics table isolated from the vacuum chamber. The Herriott Cell and plasma source are positioned on a second optics table within the vacuum chamber. The long-term drift of the optical path

length on external optics table is ±3°. After a few milliseconds, relative drift between the optic tables is much greater than the laser wavelength.

The interferometer shown in Fig. 1 uses an Ar^+ laser at 488 nm with 150 mW output power. The laser is split into a scene and a frequency-shifted reference beam using a Bragg Cell acousto-optic modulator operating at 40 MHz. The scene beam enters and exits the vacuum chamber through a quartz view port. Mirror M5 in the reference beam path facilitates adjustment of the reference path length. As passes are added within the Herriott Cell, increasing the scene beam path length, this mirror is translated to equalize the two path lengths within the 10 cm coherence length of the laser. Detection of the recombined beam is accomplished with a photodiode biased in avalanche mode, amplified, and demodulated in quadrature using standard heterodyne detection techniques.[2,7]

The Herriott Cell, within the vacuum chamber, consists of two concave mirrors facing each other in which laser light can be reflected a large number of times within the cavity. The number of reflections is determined by the mirror separation, relative tilt and laser beam entrance angles. In the general three-dimensional configuration, the beam enters the cell at an angle offset both vertically and horizontally from the mirror centerlines and the reflection points trace an ellipse on the surface of each mirror.[5,6,7] By eliminating one of the entrance angles, the passes can be confined to a single plane, ideal for measuring plasma density passing the exit plane of rocket nozzles.[2] By separating the Herriott Cell mirrors to approximately twice the focal length, and focusing the input laser onto the Herriott Cell midpoint, the beams will converge near a single point,[5,6,7] which is useful

for multi-pass measurements in small volumes. This paper focuses on the details of using the Herriott Cell in the point configuration.

2.2 Ray Tracing Analysis

In the point configuration, shown in Fig. 2, the mirrors are separated by a distance twice the radius of curvature of the mirrors. The entrance beam is passed through an achromatic lens that focuses the beam at the midpoint between the mirrors. The beam then expands until it reflects from the curved mirror. After reflection it again focuses at an axial location equal to the radius of curvature, midpoint between the mirrors. The converging-diverging behavior then repeats on each reflection. At the axial midpoint position between the mirrors the incoming beam is necessarily offset slightly in the up vertical direction from the optic axis so that the beam will strike the mirror on the right. Upon reflection this beam will be slightly offset in the down vertical direction when it is at the axial midpoint of the cell. This behavior repeats with each reflection producing a multitude of reflections between the cell mirrors. The number of passes is determined by the initial offset distance of the incoming beam. A net result is that the Herriott Cell produces two closely spaced foci, as illustrated in the expanded portion of Fig. 2. For the case of 13 passes shown in Fig. 2, one foci contains 7 passes and the other contains 6. The circles superimposed on the beam patterns are representative of the MicroPPT electrodes. The beam is removed from the Herriott Cell using a pick-off mirror and then collimated with a lens. In practice it has been possible to produce a collimated output beam from the Herriott Cell alone. Fine adjustment of mirror tilt and entrance angle have allowed the exit beam to leave the cell without refocusing from an output lens as shown

in Fig. 2. A small amount of remaining divergence is corrected with a long focal length lens placed closer to the detector. Attempts to describe this through raytracing analysis have to date proven unsuccessful, but in practice this has been a useful method of obtaining data.

Fine tuning of the number of passes can be accomplished by introducing a slight tilt in one of the Herriott Cell mirrors. Fig 3a shows a ray tracing analysis[8] of a nine-pass case where the optic axis of the right mirror is tilted up by 2.86°. Figs. 3b and 3c show the patterns for 13 and 16 passes respectively. Tilting the mirror also causes the two foci to move horizontally with respect to each other as mirror tilt increases. Depending on the application, this can limit the useful number of reflections for the interferometer. In the testing performed in this paper, the baseline case of 13 passes with the foci aligned is used.

3. Theory

The advantage of increasing numbers of passes is two-fold. First, the ability to confine multiple passes to the small volume of the MicroPPT exhaust allows high-resolution probing otherwise impossible. Second, over long timeframes, the increase in passes serves to increase the neutral density phase shift with respect to the noise of mechanical vibrations, possibly allowing late time neutral vapor measurements. This advantage is described in detail elsewhere[2] along with an analysis of the phase front distortion due to multiple reflections over a curved surface.

The interferometer provides a line averaged density measurement across a characteristic path length. In this case, the characteristic length used is the outer diameter of the MicroPPT (6.35-mm). The spatial resolution of the instrument is then only appropriate for average density measurements over the entire exit plane of the MicroPPTs. Finer detail is obtainable with the current setup. Since the point measurement geometry actually provides two foci separated by ~3 mm, there are a number of possible measurement techniques. Figure 4a shows the first configuration used. Typically, the plane of the foci is parallel to the exit plane of the thruster. With a separation of 3-4 mm between foci, the beams are located such that both foci measure over fuel on either side of the central electrode. Fig. 4b shows a case where one of the foci measures over the central electrode and the other focus measures over the fuel.

Fig. 5 shows a grid of measurement positions for the dual foci in the point measurement technique. Using Fig 4b as a starting case, measurements can be walked out from the central position, exchanging foci location outward, until a zero density measurement is achieved. The density at each point is calculated from the two measurements taken with the foci in that location. The result is a 2-D peak density plot at t=2 μs shown in Fig. 6.

This plot must be understood in terms of the following information. The thruster exit plane marks the x=0 position. Density is set to zero at the thruster exit plane. Actual data points are taken at x=1 and 5 mm and y = 0, 3, 6, and 9 mm. External density data taken at 1 mm behind the exit plane was used at point (0, 6) for consistency. The graphics program performs a linear interpolation between the data locations to construct the

contour plots. This graphical representation is an attempt to provide electron density measurements in several locations for comparison with model predictions.

4. Experimental Results

These experiments are performed at vacuum with typical background pressures of ~30 μtorr. For the interferometer, an Argon Ion laser is used at a wavelength of 488 nm. The laser enters the tank through a quartz viewport and exits through the same port as shown in Fig. 1. The cell design includes two spherical mirrors of 50.8-mm diameter with focal lengths of 101.6-mm. The plasma source for these experiments is a 6.35-mm outer diameter MicroPPT. This device is described in detail elsewhere.[9]

Figure 7 shows the density measured with the foci placements shown in Fig. 4a. Also plotted in Fig. 6 are similar results results from a two-color, flat mirror interferometer with 2 passes across the face of the MicroPPT. The thruster energy for this case is 6.6 J and typical error bars are shown. The agreement is good, and the uncertainty bars plotted are a combination of the vibrational uncertainty and the envelope of plasma source irreproducibility. The vibrational error bars this early in time are small (10^{13} cm^{-3}) so that the uncertainty seen here is dominated by the plasma source. Each of the curves is an average of 20 data shots with the error bars defined by the standard deviation. For a measurement obtained during a single discharge the two pass system has a measurement uncertainty of averaged over the thruster exit plane. With the 13-pass Herriott Cell point measurement the measurement uncertainty improves to $\pm 8 \times 10^{11}$ cm^{-3}.

A critical issue with using a large number of laser passes through the small scale length, high density plasma of the MicroPPT is whether refractive effects can divert the beam, potentially changing the number of laser passes through the plasma. The good agreement observed with the two pass measurements of Fig. 6, where the Herriott Cell mirrors were not used, indicated that the number of passes did not change due to refraction. The added passes only have the effect of increasing the instrument resolution.

5. Conclusions

The addition of a Herriott Cell to a quadrature heterodyne interferometer enables high-resolution probing of small length scale plasmas. For a single discharge the measurement uncertainty improves almost linearly with the number of laser passes through the plasma. The measurement is validated with comparison to two pass measurements, which also indicate that refractive effects in the high-density plasma are not perturbing the number of passes. The technique has broad diagnostic application possibilities including the microthrusters tested here.

6. Acknowledgements

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Figures

Figure 1: Experimental Setup.

Figure 2: Schematic of the 'point' measurement geometry with MicroPPT face for reference.

Figure 3: Beam3 traces show increasing passes by changing right mirror tilt angle. Mirror separation 406-mm.

Figure 4: Several foci locations over the thruster face.

Figure 5: Location of Herriott Cell focal points for the test matrix with cutaway from centerline to maximum radius.

Figure 6: Peak electron density ($t = 2\ \mu s$) in terms of axial and radial distance.

Figure 7: Comparison of electron density measured by a two-pass, two-color interferometer with a Herriott Cell 13 pass 'point' measurement.

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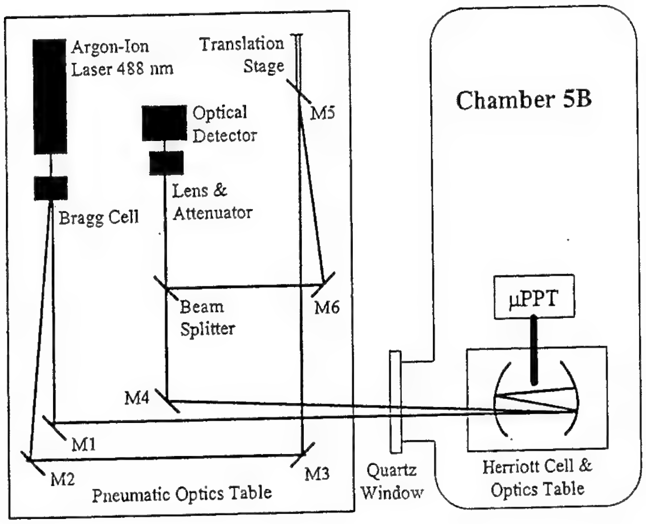
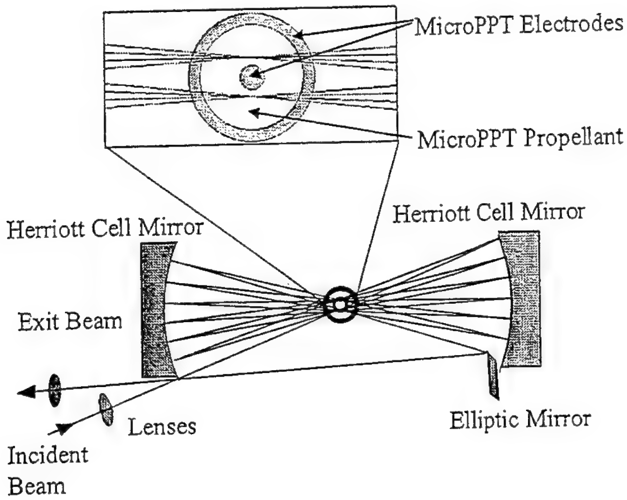


Figure 1. Antonsen *et al.*, RSI, "Herriott Cell Interferometry..."



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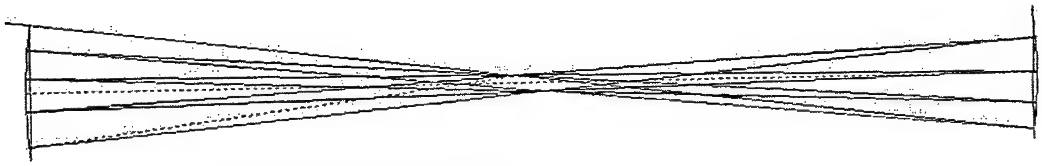
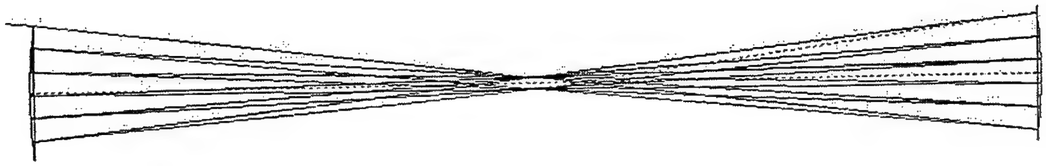


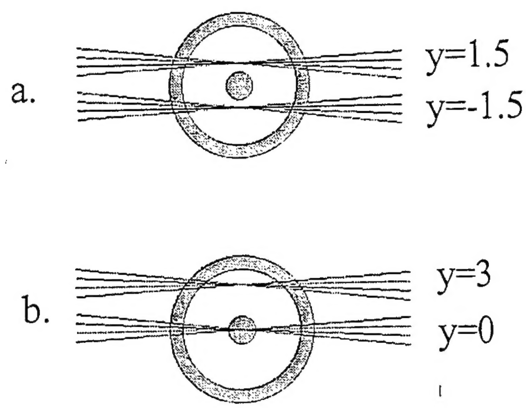
a. 9 passes, right mirror tilt angle 2.86°



b. 13 passes, no mirror tilt

c. 16 passes, right mirror tilt angle -1.15°

Figure 3. Antonsen *et al.*, RSI, "Herriott Cell Interferometry…"



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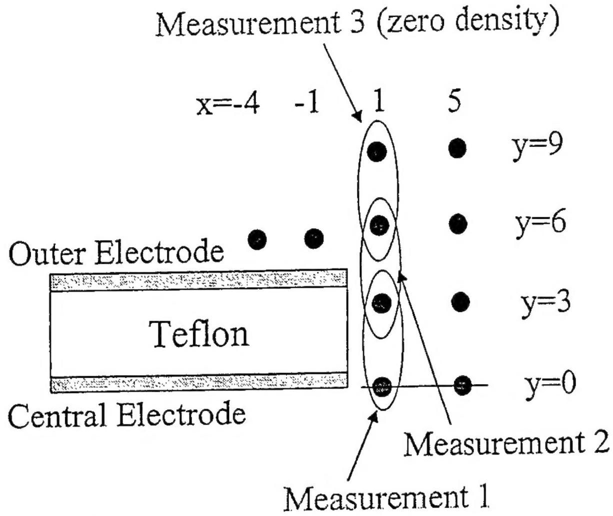

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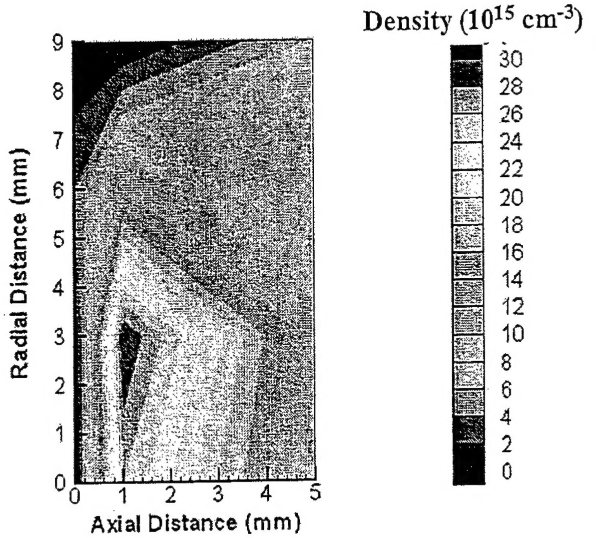

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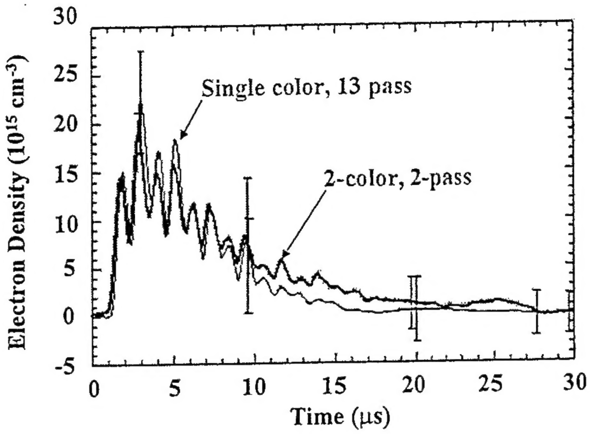

Figure 7. Antonsen *et al.*, RSI, "Herriott Cell Interferometry…"